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Modeling the tagged-neutron UXO identification technique using the Geant4 toolkit

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Abstract It is proposed to use 14 MeV neutrons tagged by the associated particle neutron time-of-flight technique (APnTOF) to identify the fillers of unexploded ordnances (UXO) by characterizing their carbon, nitrogen and oxygen contents. To facilitate the design and construction of a prototype system, a preliminary simulation model was developed, using the Geant4 toolkit. This work established the toolkit environment for (a) generating tagged neutrons, (b) their transport and interactions within a sample to induce emission and detection of characteristic gamma-rays, and (c) 2D and 3D-image reconstruction of the interrogated object using the neutron and gamma-ray time-of-flight information. Using the modeling, this article demonstrates the novelty of the tagged-neutron approach for extracting useful signals with high signal-to-background discrimination of an object-of-interest from that of its environment. Simulations indicated that an UXO filled with the RDX explosive, hexogen ($C_3H_6O_6N_6$), can be identified to a depth of 20 cm when buried in soil.

Keywords Tagged-neutron · UXO identification · Modeling · Geant4 tool kit

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Introduction

One of the major problems facing the US Department of Defense is dealing with unearthed UXO (unexploded ordnance) items at its past or present military facilities or munition testing grounds. Range clearance operations must distinguish UXO filled with high explosives (HE) from those with inert fillers, and non-destructive technologies are necessary for the cost-effective disposal of UXO during remediation of such sites. The only technique showing promise so far for the non-destructive elemental characterization of UXO fillers utilizes neutron interactions with the material. This method rests on the principle that explosives can be distinguished from each other and from innocuous materials by analyzing the quantities and ratios of carbon (C), nitrogen (N) and oxygen (O) in the material, particularly N which is unique to HE [1]. The pulsed elemental analysis with neutrons (PELAN) system exploits either or both of two types of neutron interactions with nuclei, (a) inelastic scattering and (b) capture, and then detects the induced element-specific high-energy prompt gamma-rays [2]. However, several unresolved issues hinder the wide application of this potentially very suitable technique. The most important one is that neutrons interact with all surrounding matter in addition to the interrogated material, leading to a very high gamma-ray background in the detector. Systems requiring bulky shielding and having poor signal-to-noise ratios (SNRs) for measuring elements are unsuitable for field deployment.

The inadequacies of conventional neutron interrogation methods are overcome by using the tagged-neutron approach, and the availability of compact sealed neutron generators exploiting this technique [3, 4] offers field deployment of non-intrusive measurement systems for

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14. ABSTRACT
It is proposed to use 14 MeV neutrons tagged by the associated particle neutron time-of-flight technique (APnTOF) to identify the fillers of unexploded ordnances (UXO) by characterizing their carbon, nitrogen and oxygen contents. To facilitate the design and construction of a prototype system, a preliminary simulation model was developed, using the Geant4 toolkit. This work established the toolkit environment for (a) generating tagged neutrons (b) their transport and interactions within a sample to induce emission and detection of characteristic gammarays and (c) 2D and 3D-image reconstruction of the interrogated object using the neutron and gamma-ray timeof- flight information. Using the modeling, this article demonstrates the novelty of the tagged-neutron approach for extracting useful signals with high signal-to-background discrimination of an object-of-interest from that of its environment. Simulations indicated that an UXO filled with the RDX explosive, hexogen (C3H6O6N6), can be identified to a depth of 20 cm when buried in soil.

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detecting threat materials, like explosives and drugs [5]. By accelerating deuterium ions into a tritium target, the subsequent fusion reaction generates nearly back-to-back emissions of neutrons and alpha particles of energy 14.1 and 3.5 MeV respectively. A position-sensitive detector recognizes the associated alpha particle, thus furnishing the direction of the neutron. The tagged neutrons interact with the nuclei of the interrogated object, producing element-specific prompt gamma-rays that the gamma detectors recognize. Measuring the delay between the detections of the alpha particle and the gamma-ray determines where the reaction occurred along the axis of the neutron beam (14.1 MeV neutrons travel at 5 cm ns^{-1}, while gamma rays cover 30 cm ns^{-1}). The main advantage of the technique is its ability to simultaneously provide 2D and 3D imaging of objects and their elemental composition.

To facilitate the design and construction of a prototype tagged-neutron system, a simulation model was developed, using the Geant4 toolkit [6]. The toolkit utilizes object-oriented technology and was developed at CERN, Geneva for simulating high-energy particle interactions with matter and detector responses in such experiments. It was selected in the present study for tagged-neutron simulations because of its versatile geometry, material definition packages and graphic routines which enable on-line monitoring of the geometric details of the volumes and of the particle tracks. This article describes the establishment of the toolkit environment for (a) generating tagged neutrons, (b) their transport and interactions within a sample to induce emission of characteristic gamma-rays and (c) image reconstruction of the interrogated object using the neutron and gamma-ray time-of-flight information. Further, three models have been developed in this environment to simulate the nature of the alpha-gamma coincidence time spectra and their use for isolating gamma-ray spectra of an object-of-interest from its surrounding in simple and complex situations: (i) a simulation to mimic two objects that are within the cone of tagged neutrons but separated by a finite gap between them (model 1), (ii) the two objects within the defined cone are contiguous to each other (model 2) and (iii) a common HE like RDX (hexogen, $C_3H_6O_6N_6$) is buried in soil to various depths (model 3).

Experimental

The Geant4 version 4.9.3 was implemented using Microsoft Visual C++ and Cygwin. A Lenovo T400 computer with an Intel processor running at 2.26 GHz and a 1.58 GHz, 2 GB RAM was used for the simulations.

Simulation environment

A 3D world volume was defined and all components of the system were placed within it. The neutron and alpha particle production site was placed at the origin of the world volume at the center of the box using an *x*, *y* and *z* Cartesian coordinate system where the z axis was the alpha particle and neutron directions (Fig. 1). Using particle guns designed in the Geant4 primary generator, a neutron of energy 14.1 MeV and its associated alpha particle with energy 3.5 MeV were generated at the same time and in opposite directions. The azimuthal angle φ of both particles was uniformly distributed and generated randomly within 360°. The cone angle θ_n was constrained to be no larger than ±45°. For all experiments, 100,000 alpha-neutron pairs were used. Neutrons were transported using the LHEP_PRECO_HP, Hadronic physics list. This is suitable for elastic and inelastic scattering of neutrons with energy <20 MeV and uses the G4NDL evaluated neutron data library for cross sections. The computation time was ~20 min for each run.

An alpha particle detector made up of plastic and having a diameter of 30 cm and thickness 1 cm was placed at the position (0,0,30) cm and two NaI gamma-ray detectors each of diameter 60 cm and thickness 15 cm were positioned at (50,0,30) cm and (−50,0,30) cm relative to the origin of the world volume. The large sizes of the detectors were designed for better solid angle coverage. The detectors were also defined to be sensitive so that once a particle entered the detector, it recorded all the necessary hit information such as position and time. The events in the two gamma-ray detectors were summed for enhancing the counting statistics.

Soil composition was represented by SiO_2, graphite by C and hexogen as $C_3H_6O_6N_6$ with densities 1.2, 1.7 and

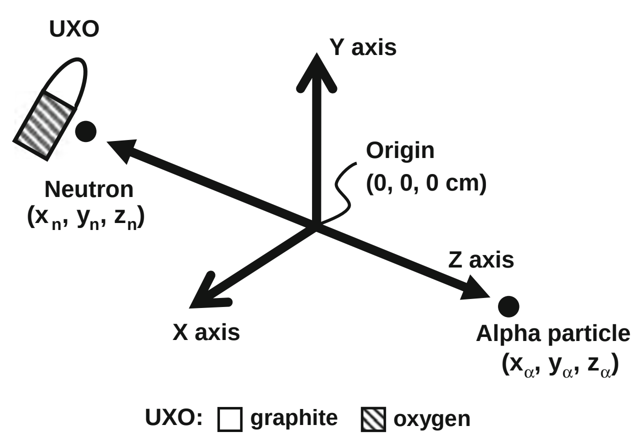

Fig. 1 Geometry of the associated-particle neutron time-of-flight technique showing the cartesian coordinate system where position sensing of the alpha particle in the (*x*, *y*) plane allows the determination of the neutron trajectory in the same plane along the *z* axis

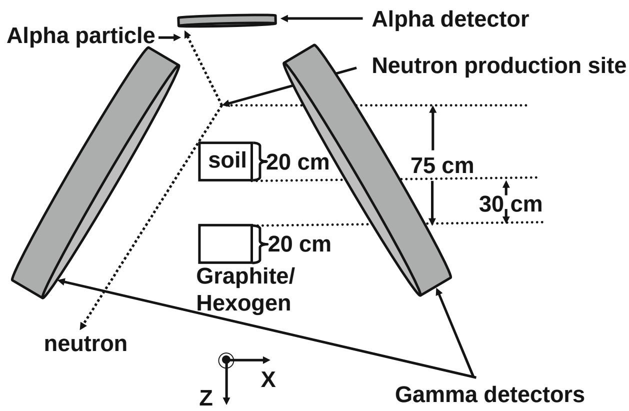

Fig. 2 Top view of the simulation environment showing the placement of objects along the neutron beam axis

1.8 g cm^{-3}, respectively. For all simulations, the object-of-interest, graphite or hexogen was 30 × 30 × 20 cm thick and placed 75 cm from the neutron production site. Model 1 and 3 had the lower surface of the soil and the upper surface of the object-of-interest separated by a distance of 30 cm (Fig. 2). Soils of different thicknesses were added layer-wise towards the neutron production site in model 3. For the contiguous case (model 2), the soil layer was displaced by 30 cm in the direction of the graphite block to make contact with it. In separate simulations, a neutron sensitive detector made up of plastic and dimensions 30 × 30 × 1 cm thick was defined to monitor the uncollided fraction of 14.1 MeV neutrons at the position of the object-of- interest. The top surface of the detector was likewise 75 cm from the neutron production site.

For simulating the imaging, the long axis of a cylindrical "bomb-shaped" object of diameter 20 cm and length, 25 cm was placed perpendicularly to the neutron beam axis at a distance of 20 cm from the neutron production site. One half of the cylinder was filled with graphite and the other half was filled with solid oxygen having density as 1.43 g cm^{-3}.

2D and 3D imaging

Using the principles of Euclidean geometry and knowing the geometrical correlations between an alpha particle and the tagged neutron (Fig. 1), the time stamping of gamma-rays and their energies as registered by Geant4 and from the known velocities of the 14.1 MeV neutron (5.1 cm ns^{-1}) and gamma-rays (30 cm ns^{-1}), the ROOT software was used to re-construct 2D and 3D images of the hypothetical UXO object.

Results and discussion

In model 1, the centers of the two objects, soil and graphite, were separated by 50 cm and the simulation correctly tracked the 14.1 MeV neutrons to the two objects; the centroids of the two neutron time-of-flight (TOF) peaks were separated by ~10 ns as predicted from theory, because the speed of a 14.1 MeV neutron is 5.1 cm ns^{-1}. Further, appropriate windows 1 and 2 of the two TOF peaks (Fig. 3a) revealed that the associated gamma-rays were from soil and graphite respectively. The characteristic

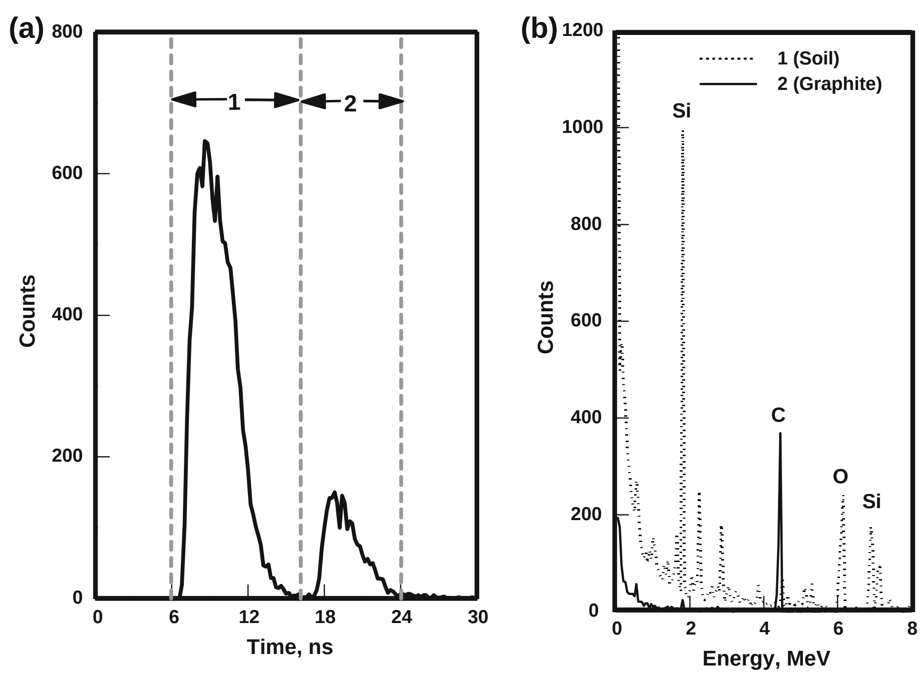

Fig. 3 Model 1, **a** Time distribution of gamma-rays from the two objects, soil and graphite when separated by a gap of 30 cm and **b** the associated time correlated gamma-ray spectra using windows 1 and 2 show that signals from the two objects in the neutron field can be completely separated

C signal at 4.43 MeV from graphite was not seen in the gamma-ray spectrum of window 1. Similarly, window 2 showed only the C signal and the soil signals were eliminated based on the neutron time-of-flight. The simulation also correctly produced the major prompt inelastic gamma-ray peaks from Si and O of soil and the single excited peak of C (Fig. 3b).

For model 2 where the two objects were in contact, the nature of the time peak changed to a single peak as expected and would be similar to the case if only one object was present at that position, i.e., the gamma-ray energies contributing to the TOF spectrum is a combination of all nuclei located in that region. However, when appropriate time slices were selected as shown in Fig. 4a, corresponding to different neutron flight-times, the associated gamma-ray energies revealed that signals from window 1 were due to the soil covering the graphite whereas signals from time window 2 were from C. It must be mentioned that the C signal intensity in window 2 is of much lower intensity compared to the gap case in model 1 because the time window selected was much narrower to eliminate the overlap region in the time peak from the two objects in the contiguous case of model 2 (Fig. 4b).

Model 3 addressed the need for the identification of UXO in the sub-surface. As a simple case, the soil cover was separated from the hexogen sample so that the time peaks from the two objects could be easily resolved as in model 1. The time peak intensity of soil increased with increasing soil layer thickness because the neutron-induced inelastic gamma-rays from the amount of soil also increased concomitantly. The time peak at ~ 19 ns representing the hexogen sample reduced progressively with increasing soil thickness (Fig. 5). This can be mainly attributed to the neutron's attenuation in soil. The variation of the neutron intensity with soil thickness as registered by the neutron sensitive detector at the hexogen position is shown in Fig. 6, along with the drop in gamma-ray intensities of C, N and O at 4.43, 5.1 and 6.13 MeV respectively. To check that these results produced by Geant4 were meaningful, the soil was replaced by various thicknesses of water and the uncollided fractions of 14 MeV neutrons were determined. The half-value thickness of 14.1 MeV neutrons in water was simulated to be 10.4 cm (Fig. 6). This compared favorably with the experimentally determined value of 9.2 ± 1.1 cm [7]. The mean

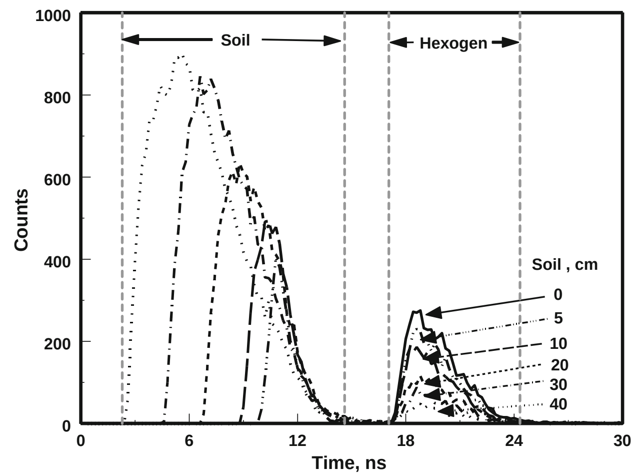

Fig. 5 Model 3—time distribution of gamma-rays from soil and the hexogen sample show the expected decrease in the hexogen time peak intensities with increasing soil thickness due to the neutron attenuation in the soil

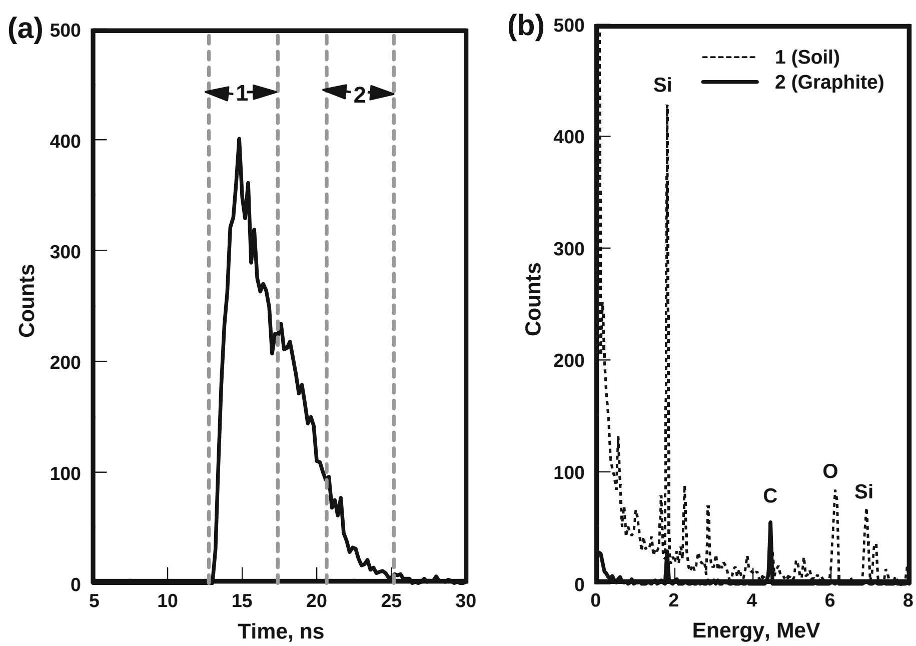

Fig. 4 Model 2, **a** Time distribution of gamma-rays for the case when the soil and graphite samples are contiguous and **b** the associated gamma-rays for time slices one and two clearly separate the signals due to the two objects

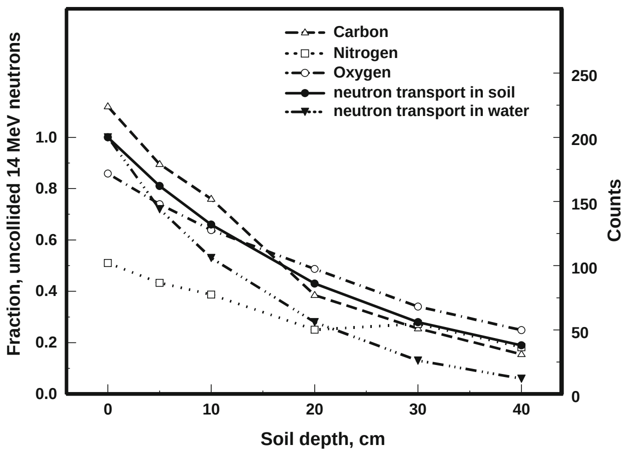

Fig. 6 The fraction of uncollided 14.1 MeV neutrons decreased with increasing soil thickness (as a result, the neutron induced gamma-ray intensities of hexogen also decreased). When the neutrons were transported in water, a half-value thickness of 10.4 cm was obtained

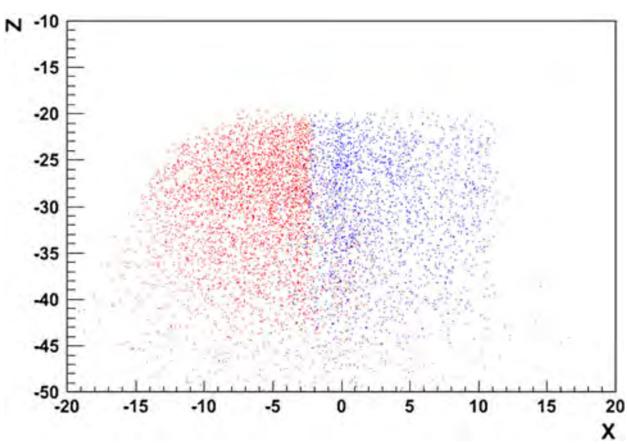

Fig. 7 2D image reconstruction of the hypothetical UXO correctly revealed it's position 20 cm away from the neutron production site in the z direction. The carbon and oxygen densities have also been isolated in their respective halves using the 4.43 and 6.13 MeV gamma lines, respectively

C/N counts ratio from the gamma-rays of hexogen associated with the neutron TOF (time window 2) was 2.76 (±0.11, CV, 3.9%) to a depth of 20 cm in soil. However, between 20 and 40 cm depth, the uncertainties in the mean value of the ratio became very significant; it was 2.45(±0.6, CV, 25%). The findings indicate that the identification of filler material will become particularly difficult for those UXO filled with HE and buried to greater than 20 cm depths in the sub-surface.

Object location and image reconstruction

The algorithm correctly located the object placed 20 cm away from the neutron production site along with its length of 25 cm and reconstructed it with the elemental densities of C and O in their respective halves as designed in the experiment. Figure 7 shows the 2D reconstruction of the object in the x–z plane which is perpendicular to the neutron beam axis.

Conclusions

The Geant4 Monte Carlo toolkit has been successfully implemented in this report to simulate a preliminary UXO sensing model and image reconstruction based on the APnTOF technique. The simulation results suggest that with the vastly improved signal-to-noise discriminations possible for measuring elemental densities, UXOs can be identified even when buried in the sub-surface to 20 cm depths. This is not possible with any conventional neutron interrogation technique. Future work will involve benchmarking the simulation results with laboratory experiments that will include simulations with realistic detector sizes and instrumental time resolutions, neutron generator dimensions and detailed gamma-ray interactions in a detector to synthesize gamma-ray spectra. It is envisioned that validation of the simulation environment will allow rapid design and development of a functional UXO sensing instrument.

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